Rendering of HDR content on LDR displays: An objective approach

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ABSTRACT

Dynamic range compression (or tone mapping) of HDR content is an essential step towards rendering it on traditional LDR displays in a meaningful way. This is however non-trivial and one of the reasons is that tone mapping operators (TMOs) usually need content-specific parameters to achieve the said goal. While subjective TMO parameter adjustment is the most accurate, it may not be easily deployable in many practical applications. Its subjective nature can also influence the comparison of different operators. Thus, there is a need for objective TMO parameter selection to automate the rendering process. To that end, we investigate into a new objective method for TMO parameters optimization. Our method is based on quantification of contrast reversal and naturalness. As an important advantage, it does not require any prior knowledge about the input HDR image and works independently on the used TMO. Experimental results using a variety of HDR images and several popular TMOs demonstrate the value of our method in comparison to default TMO parameter settings.

Keywords: HDR, tone mapping, parameter optimization, naturalness

1. INTRODUCTION

Dynamic range, i.e. the ratio between the highest and the lowest luminance, of a typical real-world scene is around 10,000:1 in orders of magnitude (or more in the presence of the source of illumination). Most of the standard imaging systems are capable to work with the dynamic range around only 100:1. Such a dynamic range compression inevitably leads to a loss of details. To resolve this issue and provide better representations of real world scenes, high dynamic range (HDR) imaging systems are being adopted. Their goal is to capture and reproduce all the details in the scene.

While obtaining an HDR content is possible for virtually everyone (either using exposure bracketing technique,[1] rendering with computer graphics tools, or using camera with HDR chip), displaying HDR scenes natively is still more or less impossible. Despite the existence of HDR displays, from which some are even commercially available*, the current technology does not permit to reproduce the range of luminance values occurring in these scenes. Moreover, the prices of HDR screens are yet to reach levels accessible for most of the consumers. These facts suggest that even though the amount of HDR content is going to grow significantly, it will be necessary to find ways to render it on traditional low dynamic range (LDR) displays. The compression of dynamic range is usually called tone mapping.

The goal of the tone mapping is to reproduce the HDR scene as faithfully as possible while preserving details and naturalness. However, these two aspects are mostly contradictory. It is therefore necessary to find a good balance between them. This could also depend on the application – while naturalness seems to be of higher importance for Quality of Experience (QoE) in multimedia,[2,3] in security surveillance it becomes secondary as it is much more important to preserve all the details.[4]

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*http://www.sim2hdr.com/

The algorithms dealing with dynamic range compression are mostly referred to as tone mapping operators (TMOs) and they can be divided into four fundamentally different categories – *global*, *local*, *gradient*, and *segmentation based*.[1] The *global* approach is the simplest as it uses the single mapping curve for all the pixel values. *Local* TMOs apply different mapping according to the pixel's neighborhood. *Gradient* operators are trying to preserve the relationships in the gradient domain and *segmentation based* operators apply different mapping according to the specific regions.

A common property of most of the TMOs is that they have (mostly several) user-adjustable parameters. These parameters serve for adapting the operator for particular displaying scenario including viewing conditions, displaying device, and, more importantly, the particular content. While this variability can be an advantage e.g. for artists, in some applications it is not practical to set all of the parameters manually. Moreover, the variability can be a problem when comparing different TMOs. In TMO comparison studies, the parameters were mostly either left in the default setting or adjusted by authors to "the highest subjective quality". The unfairness of such comparisons was already pointed out by Petit and Mantiuk[5] who used several different parameter settings for each TMO to increase the balance.

In this paper, we investigate into an objective criteria and optimization procedure to automate the process of parameter adjustment. This new method is using a two step optimization approach. In the first step, the parameters are optimized in order to minimize the contrast reversal between the HDR and LDR image, measured by a gradient based criterion. This contrast reversal value is then used as a constraint in the second step, where the naturalness is optimized. The naturalness is quantified by features (intensity, contrast, and colorfulness) found in the large set of natural images.

The next section discusses existing criteria that can be used as a base for TMO parameters optimization. Section 3 presents the measures employed in the presented method and the optimization process. The results are provided and compared in section 4 while section 5 summarizes the paper and provides the final discussion.

2. EXISTING CRITERIA FOR TMO PARAMETERS OPTIMIZATION

Objective quality assessment of tone mapped images is a challenging topic, since the dynamic range of the original image and the processed version is different. This excludes the use of typical full-reference quality metrics which do not consider such case.

The first attempt to overcome this restriction was proposed by Aydin et al.[6] Their Dynamic Range Independent Metric (DRIM) uses a visibility model from HDR-VDP-2[7] to indicate which regions contain visible contrast in HDR image and its tone mapped version. The metric then creates three distortion maps showing the regions where the contrast was either lost (i.e. contrast change is perceivable in HDR but imperceivable in LDR image), amplified (the opposite case), or reversed (the polarity is changed - mostly caused by halo artefacts) by tone mapping process. DRIM requires the prior knowledge of the precise viewing conditions and display parameters which do not necessarily must be always available. The metric was designed for qualitative analysis of the TMO performance rather than the quantitative, therefore it does not allow for calculating a single quality index. This makes it unsuitable for the purpose of parameters optimization.

Another approach was introduced by Yeganeh and Wang[8] as Tone Mapped image Quality Index (TMQI). This quality criterion consists of two parts - structural fidelity (SF) and statistical naturalness (SN). The first part is obtained by modification of popular multi-scale structural similarity index (MS-SSIM)[9] for comparing HDR and LDR images. This modification does not penalize the difference in signal strength if they are both under or over the visibility threshold. This is determined by non-liner mapping of signals' standard deviations according to the contrast sensitivity function (CSF). The second measure implemented in TMQI is based on the probability distributions of brightness and contrast (means and standard deviations) in natural grey-scale images. The weights for the two parts were determined by regression on the subjective data. Since the result is a single quality value, the method can be used for TMO parameters selection. The performance will be shown in section 4.

In our previous work,[4] we developed a parameter tuning technique for security purposes. The method looks for the parameters minimizing the area of over and under exposed regions in an image and therefore maximizing the reproduced details. However, as stated in the introduction, in multimedia applications the observers are more concerned about naturalness. Moreover, the technique works best for simpler TMOs with not many parameters as these are expected to be used in surveillance systems.

It could also be possible to employ some of the no-reference quality metrics. Since most of these measures are either designed or at least trained with respect to certain types of distortions, it is meaningful to use only distortion and opinion unaware metrics (i.e. general criteria not considering a type of distortion nor trained on dataset of distorted images). However, in our previous tests[10] we tested Natural Images Quality Evaluator[11] (NIQE) which is considered to be one of the best performing distortion and opinion unaware criteria and its results in this application did not reach the level of specialized metrics.

In the next section we introduce two novel complementary criteria suitable to be used for the TMO parameters optimization.

3. PROPOSED METHOD

The proposed method has two stages. Firstly, the parameters are optimized to result in image with minimal reversal of contrast between LDR and HDR version. Then the search for the final image continues with the constraint obtained as a tolerance with respect to the minimum contrast reversal value in order to provide higher feature naturalness.

3.1 Contrast Reversal

Most of the artefacts produced by tone mapping result in a change of the contrast. The reversal of contrast between tone mapped and original version is already used in previously mentioned DRIM[6] method. However, since a complicated model of visual system is implemented, there are several drawbacks limiting its use in optimization loop. Firstly, the computational requirements significantly prolong the searching process and secondly, the model requires setting of a number of parameters about the viewing conditions which is beneficial for proper adaptation of the content to the particular displaying scenario but can also be impractical for larger set of images and confusing for less experienced users. In our method, we therefore decided to focus more on the simplicity and computational speed.

The criterion is based on calculating the gradient in both HDR and LDR versions of the scene using horizontal and vertical Sobel kernel (computations in more directions were also tested but did not provide any additional benefit in terms of performance). Note that the gradient is computed for the luminance component of the images only. The horizontal and vertical gradient images H and V (calculated the same way for HDR and LDR image) are therefore obtained as

$$\begin{aligned} H &= Y * s_{\mathrm{h}}, \\ V &= Y * s_{\mathrm{v}}, \end{aligned} \tag{1}$$

where Y is the luminance component of the particular image, s_{h} and s_{v} represent the horizontal and vertical Sobel kernels, and the operator $*$ stands for the two-dimensional convolution.

Further on, the dominant gradient component is determined as

$$DG = \begin{cases} 1 & \text{if } |H| < |V|, \\ 0 & \text{otherwise.} \end{cases} \tag{2}$$

The $ERR1$ is defined as the change in dominant gradient component

$$ERR1 = \begin{cases} 1 & \text{if } DG(HDR) \neq DG(LDR), \\ 0 & \text{otherwise,} \end{cases} \tag{3}$$

while $ERR2$ penalizes the cases where the gradient slope is reversed, i.e.

$$ERR2 = \begin{cases} 1 & \text{if } \operatorname{sign}\{H(HDR)\} \neq \operatorname{sign}\{H(LDR)\} \text{ or } \operatorname{sign}\{V(HDR)\} \neq \operatorname{sign}\{V(LDR)\}, \\ 0 & \text{otherwise.} \end{cases} \tag{4}$$

The final contrast reversal measure is a conjunction of the two errors

$$CR = ERR1 \cup ERR2. \tag{5}$$

The index used in the optimization process is a percentage of the pixels in which the contrast reversal has been identified.

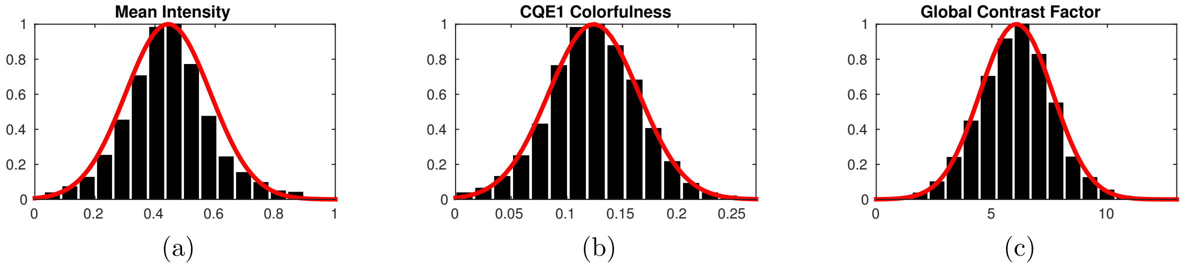


Figure 1. Probability distributions of the particular measures in 5,000 colorful natural images.

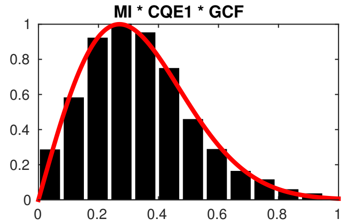


Figure 2. Probability distribution of the metrics' product for 5,000 colorful natural images.

3.2 Feature Naturalness

It is believed that the natural look of the image is a fusion of several factors.[3] The most important ones being overall luminance, contrast, and colorfulness. In our previous work,[10] we tried to identify the most suitable objective measures to estimate these features in tone mapped images. *Global Contrast Factor (GCF)*[12] has been found most appropriate to measure contrast, while *CQE1*[13] performed the best from the tested colorfulness metrics. To create a fusion, we were inspired by the procedure used for statistical naturalness part of the TMQI metric[8] development.

Firstly, we obtained 5,000 color images of different sizes and contents from a publicly available database.† Then we calculated the *mean intensity (MI)*, *GCF*,[12] and *CQE1 colorfulness*[13] for all of these images and computed their histograms to estimate the probability distributions. It can be seen from the Figure 1, that all of the used measures can be approximated by Gaussian (red curve).

In TMQI's naturalness measure, the assumption is that the intensity and the contrast are mutually independent, therefore no conditional distributions are necessary for joint distribution expression. However, this assumption is not valid when the colorfulness is added. Moreover, the conditional distributions would be very hard to estimate. We therefore tried to estimate the distribution of the criteria combination for each image (i.e. we calculated the product of the three metric values per image). The histogram is shown in Figure 2. The distribution is approximately the Rayleigh distribution as shown by the red curve in the Figure.

The probability density function (PDF) of Rayleigh distribution is defined as

$$p(x,\sigma) = \frac{x}{\sigma^2} e^{-\frac{x^2}{2\sigma^2}}, \tag{6}$$

where $x \geq 0$ and σ is a scaling factor. In our case $\sigma = 0.27$.

The Feature Naturalness (FN) is then obtained as

$$FN = \frac{p(MI \times GCF \times CQE1, \sigma)}{\max\, p(x,\sigma)}. \tag{7}$$

The denominator serves for normalization. It is the global maximum of the Rayleigh PDF with respective σ from the equation (6). The higher the FN, the more natural should the image look.

†http://www.image-net.org/

3.3 Optimization

Recall that our goal is to obtain the "best" representation of an HDR image which is suitable to be displayed on LDR displays. In the previous sections, we identified two factors, namely *CR* and *FN*, that play an important role in how a dynamic range-reduced HDR image will appear on LDR display. We, therefore, use these two factors in an effort to optimize the visual appearance of the resulting tone mapped image.

The said procedure is implemented as a constrained optimization problem. Therefore, we first obtain TMO parameter values which lead to minimum *CR*. This *CR* value is employed as a constraint in the next step of our method.

Let the $\vec{\alpha} = \{\alpha_1, \ldots, \alpha_n\}$ be the vector of TMO's parameters. The dimension of the parameter space is therefore n. Then

$$CR_{\min} = \min CR(\vec{\alpha}). \tag{8}$$

In the second stage, we search for the optimal TMO parameter values such that *FN* is maximized while the resultant *CR* is not more than $\delta\%$ larger than the minimum *CR* value ($CR_{\min}$). The optimal set of parameters $\vec{\alpha}_{\text{opt}}$ is therefore obtained as

$$\begin{aligned} \vec{\alpha}_{\text{opt}} &= \arg\max FN(\vec{\alpha}), \\ \text{s.t. } CR(\vec{\alpha}) &\leq CR_{\min} \times (1 + \tfrac{\delta}{100}). \end{aligned} \tag{9}$$

The parameter δ controls the deviation allowed from the minimum *CR* value and therefore influences the relative importance of the two measures (*CR* and *FN*). A higher value of δ gives higher importance to the *FN* measure. In this paper, we set $\delta = 5$ as this seems to provide reasonable results.

To avoid the "brute-force" approach, we also employed the Nelder-Mead downhill simplex optimization method[17] within our algorithm. The method does not use any analytical nor numerical gradients but instead directly searches for the minimum in the parameter space. The dimension of this space is defined by the number of parameters.

For our purposes we slightly modified the method so it works in the discrete parameter space rather than continuous which decreases computational requirements and the chance of ending up in the local minimum. In each step of the algorithm, when a new point of the simplex is calculated, the nearest point from the discrete space is taken. In cases where simplex becomes smaller than the step in discrete space, this could lead to false minimum detection. The stopping criterion is therefore also modified. Before the minimum acceptance, all the neighboring points are tested and if any of the points results in the smaller function value, the algorithm searches again from this starting point.

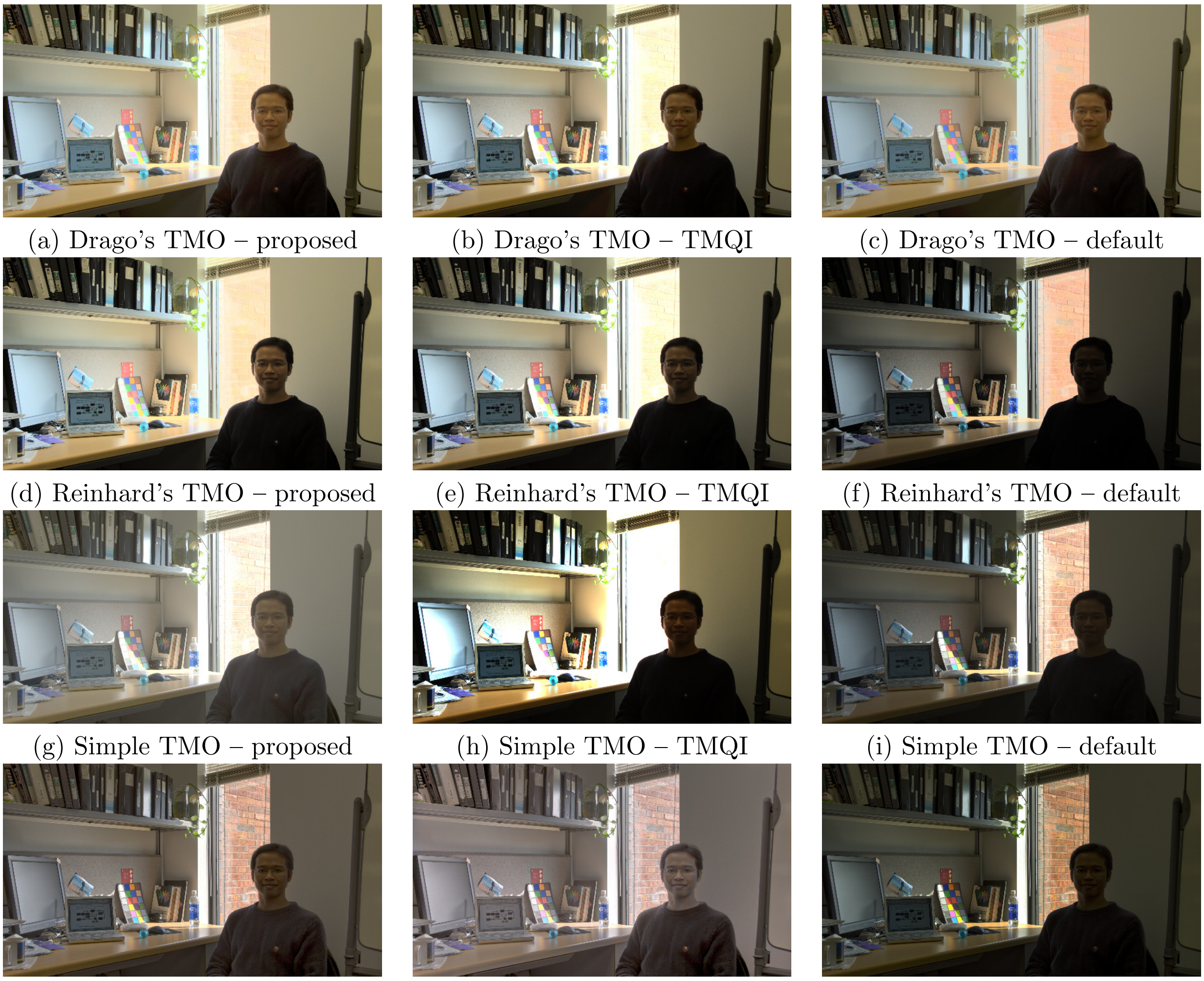
Since the Nelder-Mead optimization technique is a downhill method, the calculated FN values are negated. It is also not adapted for the constrained optimization, therefore we check in each step if the CR value for the particular point is within the required range. If not, the FN value is set to ∞.

In most of the cases, this approach was able to find similar results as if the whole parameter space was calculated but proper tests should be performed to verify it.

4. RESULTS

To properly test the proposed approach, four TMOs were used. Global operators were represented by Drago's TMO,[14] Reinhard's TMO,[15] and simple linear tone mapping with user adjustable clipping and inverse gamma correction. Selected local operator was iCAM06.[16] Implementations of Drago's and Reinhard's operators were from the Banterle's HDR toolbox.[1] Recommended gamma correction was employed after tone mapping with Drago's TMO and color correction was used after Reinhard's operator application.

Not to bias the results by utilization of certain optimization technique, the parameter space of each TMO has been sampled and all the combinations were calculated. Minimum and maximum values for proposed method as well as for TMQI were found in these spaces.



(a) Drago's TMO – proposed (b) Drago's TMO – TMQI (c) Drago's TMO – default

(d) Reinhard's TMO – proposed (e) Reinhard's TMO – TMQI (f) Reinhard's TMO – default

(g) Simple TMO – proposed (h) Simple TMO – TMQI (i) Simple TMO – default

(j) iCAM06 TMO – proposed (k) iCAM06 TMO – TMQI (l) iCAM06 TMO – default

Figure 3. "Willy Desk" image tone mapped by different TMOs with parameters set according to the proposed method, TMQI, and the default setup.

The optimal images as identified by proposed approach and TMQI for the "Willy Desk" image from the publicly available dataset[‡] per TMO are depicted in Figure 3. Each row contains the images tone mapped using particular TMO, while each column corresponds to the parameters selection method. Please note that the image was cropped to the full HD resolution prior to the processing.

From the provided example, several examples may be observed. For Drago's TMO – Figure 3(a)-(c) – the default parameters setting results in slightly unnatural reproduction of colors and TMQI gives an image with very bright background (the wall behind the window) and darker foreground (less details on the t-shirt). The proposed method's outcome provides a good compromise between the two.

Default setup of the Reinhard's TMO (Figure 3(d)-(f)) creates an image with a lot of under-exposed areas (the foreground is very dark). The result of TMQI has again high contrast between foreground and background (even more than in the previous case). Proposed technique again maintains the details and naturalness better than the two.

The proposed method applied on the Simple TMO (linear clipping and inverse gamma correction) results in the small loss of contrast compared to the other methods but with the benefit of much better details preservation.

[‡]http://rit-mcsl.org/fairchild/HDR.html

The image also looks more natural.

The only local TMO employed in this study was iCAM06. It is also the only operator that actually influences the color components as well as the luminance. Here, the benefit of using also the information about color in the proposed method is visible. TMQI provides image with higher overall luminance but the colors are very unnatural. Our technique on the other hand handles the colors in the better way and results in much more natural looking image.

To further verify the performance, we performed a preliminary subjective study with expert viewers.

4.1 Preliminary Subjective Study

The parameter selection methods described above were further compared in a preliminary subjective test with seven expert observers. All the observers are working in the field of image processing and are therefore expected to be more sensitive and reliable in comparisons. The visual acuity and correct color vision were tested prior to the study.

20 HDR images (cropped to the Full HD resolution) were tone mapped using the same TMOs as in Figure 3. The default parameters were not included in the study, thus only the proposed and TMQI methods were compared. The tone mapped versions were displayed on the 46-inch Philips 46PFL9705H Full HD displays. The displays were color calibrated. In between of these screens, the reference scene has been displayed on the SIM2 HDR47E S 4K using a dual modulation algorithm considering the PSF of the screen, local dimming, and coarse LED sampling of the HDR display. The lighting conditions were adjusted to compensate for much higher brightness of the HDR screen so the illumination behind the central screen was 100 cd/m^2 resulting in the reflected diffused light behind the LDR screens to be around 50 cd/m^2. The viewing distance was three times the screen height (which is similar for both HDR and LDR displays).

The observers were asked to compare the images obtained via the proposed parameters selection method and via the TMQI maximization. For this they were instructed to:

1. Check if the two side images are perceptually different. If not, press "down" on the keyboard.
2. If the images are different, select the one which is perceptually closer to the reference.

The possible outcome of each comparison is therefore either that the two images are similar or the better image is labelled. The results are shown in Table 1. The numbers show how many times the particular method was preferred for the respective image (or how many times were the images labelled as the same).

The last row sums up the cases. It can be observed that the results are much more discriminative for iCAM06 and simple linear TMO with inverse gamma correction. For the iCAM06, the reason lies probably in adjustment of the color reproduction which is not considered in TMQI and the optimization can therefore lead to some colorfully unnatural outcomes. The simple TMO with maximized TMQI on the other hand tend to have high contrast but in exchange for the loss of details. The proposed method seems to handle the trade-off better for the tested set.

The results for Drago's TMO are less convincing (more than the third of the images were evaluated as the same), nevertheless the performance of our method seems to be comparable or better than maximization of TMQI. It is true that for this operator the outcomes change the least with the change of parameters, hence the high number of the similar images.

For the Reinhard's operator, both methods lead to very similar total number of preferences but there are some differences depending on the content. This is probably caused by the fact that the outcomes from this TMO were mostly the least similar to the original as displayed on the HDR screen. Then the task of selecting the closer image became more challenging for the observers and the result is inconclusive.

By all means, this study is not exhaustive. The test with higher number of observers should be performed to reliably prove the superiority of the proposed technique. However, the results of such a preliminary study can provide valuable clues about the trends and suggest that the approach is promising.

Table 1. The results of the subjective test. The numbers show how many times the particular method was preferred for the respective image (or how many times were the images labelled as the same).

	Drago			iCAM06			Reinhard			Simple		
Im. #	Proposed	TMQI	Same	Proposed	TMQI	Same	Proposed	TMQI	Same	Proposed	TMQI	Same
1	5	0	2	0	0	7	2	2	3	5	2	0
2	0	0	7	4	0	3	5	2	0	6	1	0
3	2	2	3	7	0	0	1	6	0	6	0	1
4	1	6	0	7	0	0	2	4	1	5	2	0
5	0	0	7	7	0	0	2	4	1	6	0	1
6	6	1	0	7	0	0	0	0	7	0	0	7
7	0	0	7	6	0	1	2	5	0	7	0	0
8	5	1	1	7	0	0	7	0	0	7	0	0
9	4	3	0	4	1	2	4	1	2	6	1	0
10	5	0	2	3	0	4	5	1	1	5	2	0
11	0	0	7	3	0	4	2	1	4	7	0	0
12	2	5	0	4	0	3	1	6	0	5	2	0
13	1	5	1	2	5	0	0	6	1	2	3	2
14	4	1	2	2	1	4	6	0	1	7	0	0
15	5	2	0	7	0	0	3	0	4	7	0	0
16	0	0	7	3	2	2	2	3	2	7	0	0
17	1	4	2	5	1	1	3	4	0	0	4	3
18	4	3	0	0	0	7	2	3	2	5	2	0
19	3	1	3	6	0	1	2	0	5	3	0	4
20	5	1	1	4	1	2	2	5	0	6	1	0
ALL	**53**	35	52	**88**	11	41	**53**	**53**	34	**102**	20	18

5. CONCLUSION

A novel objective parameters optimization method for rendering HDR images on LDR screens has been proposed. The method is based on minimizing the contrast reversal with simultaneous naturalness preservation which is measured by the fusion of certain features (namely overall image intensity, contrast, and colorfulness).

The technique focuses on simplicity and low computational complexity (although it is necessary to provide at least approximate range of parameters for the given TMO). It also does not consider the limitations of the human visual system and displaying conditions (the contrast reversal measure can therefore sometimes penalize even the cases where the reversal is not perceivable by the human eye). The used assumptions are intended to be as universal as possible.

The technique has been compared to the maximization of TMQI[8] for four TMOs (three global and one local operator). A preliminary subjective study with seven expert observers has been conducted on 20 HDR images. The results suggest that this approach brings several advantages, especially in the cases where color information is being processed. The future work can include proper subjective study for the performance verification, possibly including more TMOs. Other optimization techniques can also be adapted and tested.

ACKNOWLEDGMENTS

The work was partially supported by the SGS15/091/OHK3/1T/13 project of the Student Grant Agency of CTU in Prague and the project GA14-25251S Nonlinear imaging systems with spatially variant point spread function of the Czech Science Foundation.

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